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Governing Transactions and Interdependences between Linked Value Chains in a Circular Economy: The Case of Wastewater Reuse in Braunschweig (Germany)

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Abstract: Reusing wastewater in agriculture has attracted increasing attention as a strategy to support the transition towards the circular economy in the water and agriculture sector. As a consequence, there is great interest in solutions for governing the transactions and interdependences between the associated value chains. This paper explores the institutions and governance structures for coordinating transactions and interdependences between actors in linked value chains of wastewater treatment and crop production. It aims to analyze how transactions and interdependences shape the governance structures for reusing wastewater at the local level. A transaction costs analysis based on data from semi-structured interviews and a questionnaire is applied to the agricultural wastewater reuse scheme of the Wastewater Association Braunschweig (Germany). The results show that different governance structures are needed to match with the different properties and requirements of the transactions and activities between linked value chains of wastewater treatment and crop production. Interdependences resulting from transactions between wastewater providers and farmers increase the need for hybrid and hierarchical elements in the governance structures for wastewater reuse. The authors conclude that aligning governance structures with transactions and interdependences is key to efficiently governing transactions and interdependences between linked value chains in a circular economy.

Keywords: agriculture; wastewater reuse; irrigation; value chains; linkage; interdependence; institutions; governance structures; transaction costs; circular economy

1. Introduction

Increasing waste production and the scarcity of natural resources are expected to aggravate with growing populations and consumption. For this reason, solutions for reducing waste and recycling and reusing materials are gaining importance. In this context, the concept of the circular economy has attracted increasing attention from policy, science, business, and civil society. The circular economy is often characterized as an “industrial economy that is restorative or regenerative by intention and design” [1] (p. 7). In contrast to the largely linear “take-make-use-dispose” economic model, the circular economy aims to minimize waste and to keep the value of products, materials, and resources in the economy for as long as possible [2].

Moving towards a more circular economy could provide many opportunities, including reduced pressures on the environment, enhanced security of supply of raw materials, increased competitiveness, innovation, growth, and jobs [2,3]. However, the transition towards a circular economy is challenging, since it requires, among other things, finance, economic enablers, and technical skills, as well as fundamental changes in consumer behavior, business models, and last but not least, institutions and governance at all levels [3]. The European Commission has addressed these issues by presenting an action plan including legislative proposals on EU waste policy, areas for actions, and specific measures to promote the implementation of the circular economy [2]. One of the areas for action proposed in the plan is the promotion of reusing treated wastewater in agriculture.

In safe conditions, the reuse of wastewater presents an opportunity to reduce the demands on natural water resources and the discharge of pollutants to surface water bodies [4]. Furthermore, it can increase crop yields [5–7] and reduce purification levels and wastewater treatment costs [8–10]. Since wastewater supplies nutrients, it can also reduce the application of mineral fertilizer and decrease fertilization costs [9,11]. Concerns about the reuse of wastewater in agriculture include potential health risks for farm workers and food consumers [12,13], soil salinization [14], and the accumulation of hazardous substances in soil and crops [13,15–19]. When reusing wastewater for irrigation, adequate risk management strategies, including the application of proper purification levels, periodic monitoring of soil and crop properties, as well as suitable irrigation, cultivation, and harvesting practices, are indispensable to minimize hazards to humans and the environment [4,14,20,21].

Reusing wastewater in agriculture is characterized by transactions between the value chains of wastewater treatment and crop production, like the irrigation of wastewater for cultivating crops. The transactions create linkages and interdependences between the value chains due to shared resources (e.g., land), input–output relations (e.g., water and nutrients), and interdependences of activities and actors (e.g., interdependence of irrigation and crop cultivation practices and the respective providers and users of water) [9]. As a result of such linkages and interdependences, linked regional value chains and value cycles may develop [9]. Empirical studies show that value chains integrated within local economic cycles can reduce costs [22] and contribute to an increment of added-value for regional economies [23–26]. Findings from an added-value analysis provide evidence that linking the value chains of wastewater treatment and crop production by reusing wastewater can conserve natural resources and lead to significant cost savings, added-value gains, and a high share of local added-value [9].

However, despite the benefits associated with wastewater reuse, there is still no widespread implementation of wastewater reuse applications in the European Union [27]. Studies on the reuse of wastewater show that the challenges for implementing more reuse applications lie, among others, in the design of institutions and governance structures for reusing wastewater [27–32]. At the EU level, no common standards or quality guidelines for wastewater reuse have been implemented yet [28,33]. Instead, member states are expected to adopt the requirements of various EU directives correlated with water reuse applications due to health and environmental concerns [28,33]. The principal directives with implications for wastewater reuse are the *Water Framework Directive* and the *Urban Waste Water Treatment Directive*. The *Water Framework Directive* establishes “a framework for action in the field of water policy and indirectly recognizes reuse as a strategy for increasing water availability, which thereby contributes to the good quality status of water bodies” [33] (p. 560). The *Urban Waste Water Treatment Directive* concerns the quality of wastewater discharged to receiving waters and states that “treated wastewater shall be reused whenever appropriate” [34] (p. 4). This implies that “wastewater reuse is acceptable in as much as it does not breach other EU legislation or national laws” [33] (p. 560). Other directives containing provisions that are relevant to water reuse include the *Groundwater Directive*, the *Drinking Water Directive*, the *Sewage Sludge Directive*, the *Nitrates Directive*, the *Thematic Strategy for Soil Protection*, the *Bathing Water Directive*, the *Freshwaters Fish Directive*, the *Habitats Directive*, and the *Industrial Emissions Directive* [28]. Remarkably, none of the directives “is directed at regulating or supporting water reuse as such” [33] (p. 561). Moreover, the non-existence

of common criteria at the EU level for managing health and environmental risks related to water reuse is a cause of mistrust in the safety of water reuse practices and thus, one of the main obstacles for water reuse in Europe [33,35]. The EU Commission aims to overcome this barrier by proposing EU minimum quality requirements for water reuse in agricultural irrigation and aquifer recharge [35]. However, the proposed requirements are still being discussed [36] and have not yet become legally binding.

With the growing need for a transition towards a circular economy and the potential of wastewater reuse in terms of economic and environmental benefits, there is an increasing interest not only in developing common wastewater reuse criteria at the EU level, but also in appropriate governance solutions for wastewater reuse and interdependent value chains at the local scale [9]. This requires more research on the governance structures for reusing wastewater including analysis of the specific transactions and interdependences between the value chains of wastewater treatment and crop production and analysis of the alignment of governance structures with transactions and interdependences. The alignment of governance structures with transactions is essential since misalignments can result in lower profitability and higher failure rates [37–40].

Existing studies on the governance of wastewater reuse have analyzed different applications for wastewater, including agricultural uses as well as urban, industrial, and potable uses. The studies have focused either on collaboration and risk management [41], or referred predominantly to the institutional challenges for the wastewater reuse sector at higher levels of governance, including regulatory and legislative issues at the national and international level [28,29,33,42–45]. Only a few researchers have analyzed the institutional arrangements for reusing wastewater for agricultural purposes at the local level [30–32]. Consequently, the empirical basis for deriving conclusions and recommendations for the governance of wastewater reuse at the local level is scant. Saldías et al. [31] analyzed the indirect and unplanned agricultural wastewater reuse in Hyderabad (India) and found that the ambiguous objectives of institutions, fragmentation among or within institutions, and a lack of regulatory enforcement are major constraints for developing formalized practices. A study by Al-Khatib et al. [30] investigated governance-related factors that influence the reuse of treated wastewater for irrigation in Jericho (Palestine) and identified overlapping and unclear responsibilities among actors, the absence of laws, as well as overlapping and conflicting provisions as obstacles for the reuse of wastewater. Saldías et al. [32] explored the institutional arrangements for a self-managed agricultural wastewater reuse scheme in Western Cape (South Africa) and identified the presence of an effective policy and regulatory framework as a key requirement for the successful implementation of the scheme.

However, from an institutional economic perspective, there is a clear gap in the current research on the design of governance structures for reusing wastewater at the local level. The body of literature is lacking in the characterization of the specific transactions between the value chains of wastewater treatment and crop production according to their properties, the analysis of the governance structures regarding their features and the consideration of the interdependences between the actors involved. Furthermore, the research on wastewater reuse has not yet addressed the alignment of governance structures with transactions and interdependences between actors. As a result, the understanding of the governance structures for coordinating the specific transactions that create linkages and interdependences between the value chains of wastewater treatment and crop production is insufficient. In particular, to the best of our knowledge, no previous studies have analyzed how transactions and interdependences between wastewater providers and crop producers shape the governance structures for wastewater reuse and how the alignment between governance structures with the transactions and interdependences facilitates reusing wastewater at the local level.

The present paper seeks to address this gap by looking at the specific transactions and activities in the agricultural wastewater reuse scheme of the Wastewater Association Braunschweig (Germany) which uses treated municipal wastewater to irrigate food and energy crops. We aim to analyze empirically the interplay of the transactions and interdependences between the actors with the

institutions and governance structures of the reuse scheme. In particular, the study will answer the following research questions:

- (1) How do the properties of the transactions and the interdependences of actors shape the governance structures for reusing wastewater?
- (2) How does the alignment of the governance structures with the transactions and interdependences contribute to the smooth operation of agricultural wastewater reuse schemes?

We assume that by better understanding how governance structures are shaped by transactions and interdependences between actors we can contribute to developing appropriate governance structures for wastewater reuse in a circular economy at the local scale. Moreover, understanding the alignment of governance structures with transactions and interdependences of actors may help to improve the performance of wastewater reuse schemes in a circular economy. With this paper, we seek to introduce a novel perspective in the discussion on governance structures for linked value chains—i.e., the perspective of transaction cost economics—which offers new possibilities for analyzing and interpreting circular economies.

The rest of the paper is structured as follows: Section 2 describes the conceptual and theoretical framing of the research with emphasis on the transaction cost theory. Section 3 introduces the case study and explains the methods employed for the collection and analysis of data. Section 4 presents the empirical findings from analyzing the case study, including a detailed description of the core characteristics of the actors, transactions, and institutional arrangements of the wastewater reuse scheme in Braunschweig. In Section 5, we discuss the results according to the research questions and the lessons learned for governing transactions and interdependences between linked value chains in a circular economy. In this section, we also discuss the research design and suggest future research directions.

2. Conceptual and Theoretical Framing

The conceptual and theoretical framing of this research draws on several concepts and theories described in the following sections, including the concept of linked and interdependent value chains in a circular economy, the related concepts of transactions, institutions, and governance structures in action arenas and action situations, as well as the theory of transaction cost economics.

The concept of the circular economy is a very young research field that “still requires development to consolidate its definition, boundaries, principles and associated practices” [46] (p. 703). A multitude of different circular economy definitions, varying with the actors and point of view, has been developed [1,2,46–51] but no commonly accepted definition has become established yet [46,52]. Several authors stress that the lack of a commonly accepted and shared definition could lead the circular economy discussion to a conceptual deadlock [46,49]. Bearing this in mind, Kirchherr et al. [49] encourage scholars to deliberate on the circular economy concept through the explicit adoption of a circular economy definition to facilitate cumulative knowledge development on the topic. In the study at hand, we refer to the definition of Kirchherr et al. [49] (pp. 224–225), who describe a circular economy as “an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations.” The circular economy “is enabled by novel business models and responsible consumers” [49] (p. 229). We adopt this definition for our research as a working definition, since it provides a brief but comprehensive depiction of the core characteristics of the circular economy concept, including its principles, operating levels, aims, and associated implications and enablers. It is important to understand that moving towards the circular economy implies “a fully systemic change, affecting all stakeholders in the value chain” [53] (p. 12).

We note that “a circular economy goes beyond the pursuit of waste prevention and waste reduction to inspire technological, organizational and social innovation across and within value chains” [53] (p. iv).

Applying the thinking of the circular economy to water means to transform the conventional linear water use model—which is based on extracting, treating, distributing, consuming, collecting, treating, and disposing water—into a circular water use model [54]. In such a model, “wastewater is not considered as waste but rather as a valuable non-conventional resource” [55] (p. 229) that can generate additional added-value [9,22], and that should be circulated to preserve natural resources of water and nutrients [55]. In contrast to the linear model where water becomes successively polluted [56], the circular water use model aims at reducing pollution [57]. Further aims of the circular water economy are the reduction of freshwater demand, the reuse of wastewater [57–59], and increased retention of water [57]. We refer to this model but focus only on the reuse of wastewater in agriculture. Figure 1 shows the flow of water in the linear water use model, in contrast to the wastewater reuse model with crop production. The figure indicates that human water consumption is based on the treatment and distribution of water resources extracted from the natural system. After consumption, wastewater is ideally collected for treatment. Subsequently, the treated water is used in two different ways depending on the economic water use model. In the linear model the treated water leaves the economy via disposal without further use. In this case, crop production depends exclusively on extracting water from the natural system. By contrast, in the wastewater reuse model the treated wastewater circulates in the economy through various options for reuse [59], including crop production. In this case, the figure shows that the reuse of treated wastewater is an option for turning wastewater into a resource and reducing the demand for natural fresh water resources in crop production.

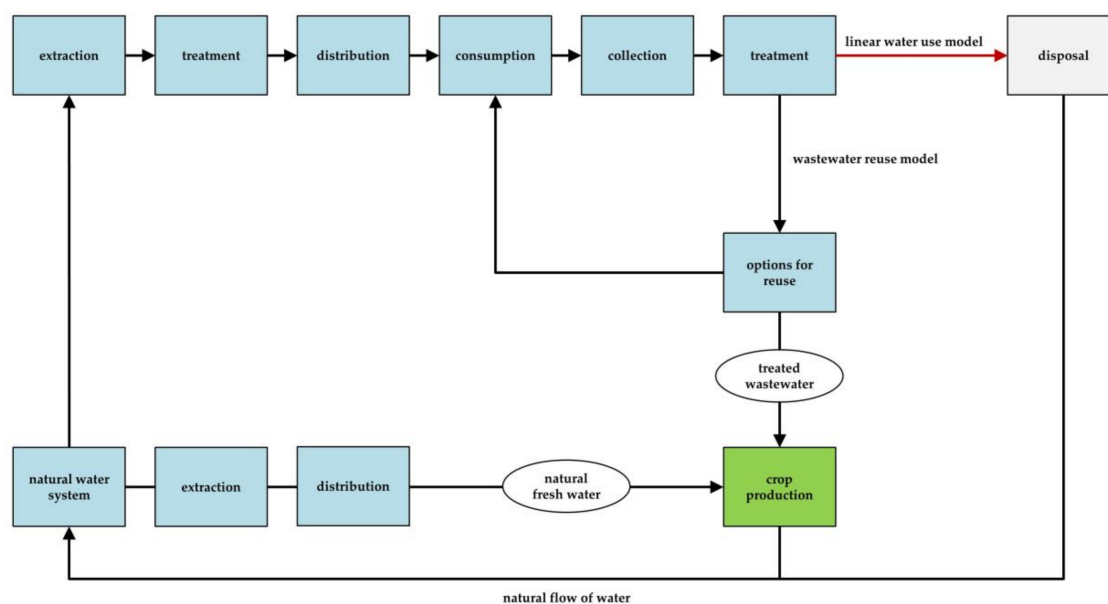


Figure 1. Flow of water in the linear water use model and in the wastewater reuse model with crop production.

Our approach for analyzing the reuse of wastewater in the circular economy is based on the concept of value chains, and focuses on the linkages and interdependences between the value chains of wastewater treatment and crop production at the local level. Value chains include “the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use” [60] (p. 4). In the case of wastewater reuse in agriculture, several goods and services are produced, including treated water and crops. Commonly, these goods pertain to distinct value chains. In the scrutinized case of wastewater

reuse in agriculture, however, the production of treated water and crops goes together. This leads us to assume linkages and interdependences between the value chains of wastewater treatment and crop production in the scrutinized case. These interdependences may be due to the joint use of resources (e.g., land), the sharing of substances through input–output relations (e.g., water and nutrients), as well as immaterial interactions and interdependence of activities and actors (e.g., interdependence of irrigation and crop cultivation practices’ respective providers and users of water) [9].

The linkages and interdependences between the value chains are believed to result from different physical and social processes taking place in distinct action situations located in various action arenas (The terms “action arena” and “action situation” originate from the Institutional Analysis and Development framework (IAD) developed by Ostrom [61]. We adopt the terms and related definitions for this research but do not further refer to the IAD framework.). An action arena is defined as the “conceptual space in which actors . . . make decisions, take action, and experience the consequences of these actions” [62] (p. 20). The action arena includes one or multiple action situations and the actors who interact in the action situation regarding activities and/or transactions [62]. The action situation refers to the “social space where participants . . . interact, exchange goods and services, solve problems, dominate one another, or fight (among the many things that individuals do in action arenas)” [61] (p. 14).

In the present study, we conceptualize the agricultural reuse of wastewater as an action arena which is composed of three sub-arenas: (1) the provision of wastewater through the value chain of wastewater treatment; (2) the use of the wastewater as input in the value chain of crop production; and (3) the transference of wastewater between both value chains (Figure 2). The actors in all three sub-arenas participate in various action situations. Action situations associated with reusing wastewater in agriculture include, for instance, provision situations in which actors provide resources and services (e.g., land, water or irrigation service), distribution situations where actors define the allocation of resources (e.g., distribution of wastewater between farmers and plots) and appropriation situations in which actors make use of resources (e.g., use of wastewater and land for cultivating crops).

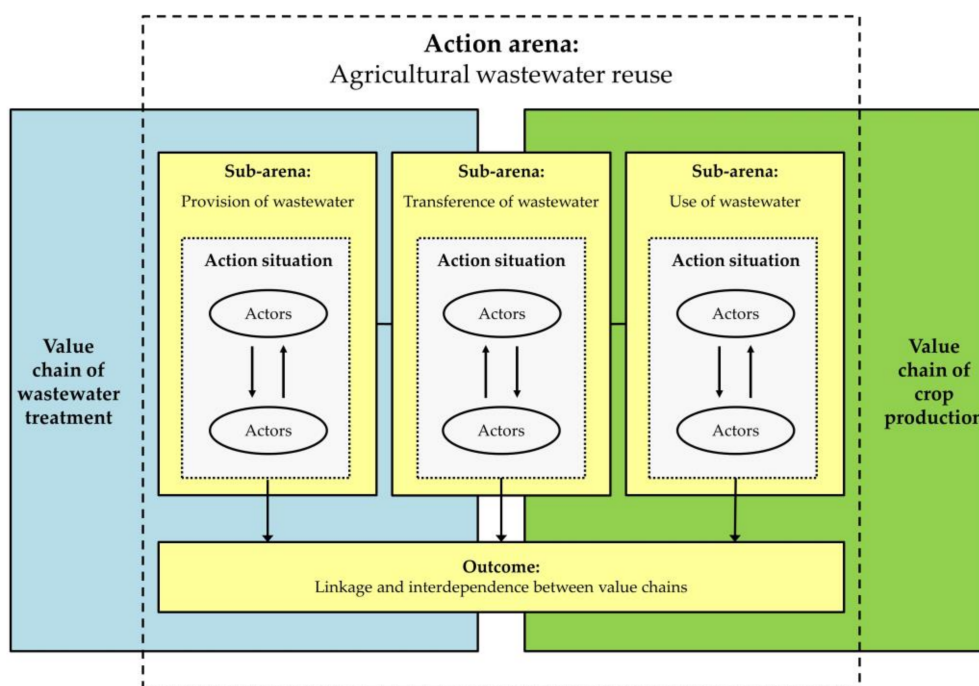


Figure 2. Conceptual framework for analyzing the agricultural reuse of wastewater.

The theory of transaction cost economics was chosen as the theoretical framework for understanding the alignment of transactions and governance structures in linked value chains. Researchers have used this framework to analyze various problems related to the economics of organization and contractual relationships [38,63]. Transaction cost theory has also been used in many empirical studies for explaining phenomena of agricultural supply chains [64–71]. The main goal of analyses based on the transaction cost theory is to assess the relative efficiency of organizing transactions while assuming that actors are rationally bound and tend to behave opportunistically. In our present research, we use the insights from the transaction cost theory to analyze the transactions and governance structures linking value chains in a circular economy for reusing wastewater and sewage sludge in agriculture. The basic unit of analysis is the transaction defined as “an exchange which occurs between two stages of the production/distribution chain as the product changes in form and/or in ownership rights” [72] (p. 17). The transaction cost theory emphasizes that transactions are associated with transaction costs because they require information, negotiation and conclusion of agreements, monitoring and enforcing compliance with those agreements, as well as adaptation of agreements [73,74].

Transactions differ mainly with respect to the three properties of asset specificity, uncertainty, and frequency, from which “the condition of asset specificity is the most important” [75] (p. 366). Asset specificity matters when actors invest in specific assets and refers to “the degree to which an asset can be redeployed to alternative uses and by alternative users without sacrifice of productive value” [76] (p. 59). The fundamental consequence of investing in specific assets is the creation of a condition of bilateral dependency which may allow actors to opportunistically siphon off the quasi-rents of the actors who made transaction-specific investments [77]. The property of uncertainty in transactions refers to the difficulties of anticipating exogenous disturbances and to predict whether the exchange partners may behave opportunistically [78]. Frequency indicates how often a certain transaction is repeated.

Transactions may cause interdependences between value chains, when actors or actions are affected by or depend on each other’s actions [79,80]. Interdependences between value chains or actors may result “in either conflicts to be solved or opportunities for cooperation” [81] (p. 363). In order to mitigate conflicts and to realize gain from cooperation, actions and transactions leading to interdependences need to be regularized by institutions and governance structures [81]. “Institutions are the rules of the game of a society or, more formally, are the humanly devised constraints that shape human interaction” [82] (p. 3). Institutions can be either formal (e.g., laws, ordinances, etc.) or informal (e.g., norms, values, and conventions). In order to implement and enforce institutions, adequate governance structures are necessary. Governance structures are conceptualized as “organizational solutions for making institutions effective, i.e., they are necessary for guaranteeing rights and duties and their use in coordinating transactions” [81] (p. 360). The structures present distinct features such as incentive intensity, administrative control, capacity for autonomous and coordinated adaptations and contract law [77].

The feature incentive intensity of a governance structure characterizes the magnitude of the motivation of the transactional partners to be efficient and adapt to changing conditions [83]. Strong incentives are those provided by transactions in which gains from efficiency improvements flow directly to the individuals who contributed to the improvement. They stimulate individuals to innovate and increase efficiency. Weak incentives, by contrast, are those associated with transactions in which individuals can not personally lay claim to the gains from efficiency improvements [84,85]. The degree of administrative control in a governance structure describes to what extent hierarchical instructions and monitoring of activities are used for directing the actor’s activities and efforts, in particular, for adapting to changes and for preventing actors from behaving opportunistically [83]. The autonomous adaptability characterizes how easy the transactional partners can adapt to changes independently from each other within a given governance structure. By contrast, coordinated

adaptability describes the supportiveness of a given governance structure towards coordinated adaptations between transacting individuals [83].

Scholars categorize governance structures according to these features along a spectrum ranging from the pure, anonymous spot market to the completely integrated firm (hierarchy) [71,77,86]. Between these two pure forms of governance structures there is a continuum of hybrid (or intermediate) types of governance structures including various forms of long-term contracting, clusters, networks, symbiotic arrangements, supply chain systems, franchise arrangements, partnerships, cooperatives and alliances among firms [70].

Market governance structures are characterized by strong incentives and weak administrative control. The structures strongly support autonomous adaptations based on a strong legalistic contract law regime. In contrast, hierarchical governance structures are characterized by weak incentives and strong administrative control. They are strongly supportive to coordinated adaptations, and they are further characterized by a weak contract law regime [77]. Hybrid governance structures show “intermediate values in all features” [76] (p. 104) that describe markets and hierarchies. They are characterized by “semi-strong incentives, an intermediate degree of administrative apparatus, display semi-strong adaptations of both kinds, and work out of a semi-legalistic contract law regime” [76] (p. 281). Table 1 summarizes the distinguishing features of market, hybrid, and hierarchical governance. It shows that an increase (decrease) in intensity in one feature is accompanied by a decrease (increase) of intensity in another feature.

Table 1. Distinguishing features of market, hybrid, and hierarchical governance structures [77].

Features	Governance Structure		
	Market	Hybrid	Hierarchy
Incentive intensity	++	+	0
Administrative control	0	+	++
Autonomous adaptation	++	+	0
Coordinated adaptation	0	+	++
Contract law	++	+	0
++ = strong + = semi-strong 0 = weak			

Ménard [70] identified three empirical regularities within the great heterogeneity of hybrid governance structures: First, resource users in hybrid arrangements pool some of their resources but keep the associated ownership and decision rights distinct. Second, the coordination of the resource users in hybrids relies usually on contracts providing only a general framework which remains highly incomplete. Third, resource users in hybrids compete with each other as well as with other hybrid arrangements and other types of organization.

Transaction cost economists evaluate the relative cost-efficiency of coordinating transactions by assessing the fit between the properties of the transaction and the associated governance structure. They refer to the discriminating alignment hypothesis which predicts that “transactions, which differ in their attributes, are aligned with governance structures, which differ in their costs and competencies, in a discriminating (mainly transaction-cost-economizing) way” [77] (p. 277). In other words: actors will ideally assign transactions to the governance structure that minimizes transaction costs. Yet which governance structure fits with which kind of transaction? The transaction cost theory predicts that the market is the most efficient governance structure for non-specific transactions. By contrast, if the degree of asset specificity and uncertainty increases, it will be more efficient to organize the transaction in a hybrid or even in a hierarchical governance structure. Hybrids are efficient in coordinating transactions when relation-specific investments are strong enough to “generate substantial contractual hazards without justifying integration and its burdens, and when uncertainties are consequential enough to require tighter coordination than what markets can provide” [87] (p. 31). For transactions that are

characterized by high degrees of asset specificity, transaction cost theory recommends organizing transactions in a hierarchy in order to minimize transaction costs [77].

3. Materials and Methods

We have chosen a qualitative research approach based on case study methods [88–91] for analyzing the governance structures for transactions and interdependences between actors in linked value chains of wastewater treatment and crop production. Qualitative research on case studies is commonly proposed by researchers for studying socioeconomic phenomena with a rather small number of observations [92], such as the combination of wastewater treatment and agricultural value chains. It allows researchers to study the complex nature of linked value chains in depth, as it facilitates describing transactions and governance structures regarding their characteristics and identifying different perceptions, attitudes and motivations that underlie and influence the behavior of the actors involved [93].

3.1. Case Study

The case study chosen for the analysis is the agricultural wastewater reuse scheme of the city of Braunschweig in Germany. This reuse scheme has gone through several developmental phases resulting in the combination of agricultural reuse of wastewater and sludge, crop production, and bioenergy production. The reuse scheme is managed by the Wastewater Association Braunschweig which was founded in 1954 with the aim of implementing a large-scale agricultural wastewater irrigation system in the region of Braunschweig. Since then, the reuse scheme has developed into a complex net of linked activities at regional level with various environmental and economic benefits [9]. The members of the association are the city of Braunschweig, the water board of the neighboring city Gifhorn, and 90 farmers with agricultural land in the association territory.

The scheme treats the municipal wastewater of the cities of Braunschweig and some neighboring communities. A full biological treatment process produces purified wastewater which is delivered for reuse from the treatment plant to a selected territory covering a coherent area of 2700 ha of cropland with infrastructure facilities for irrigation (e.g., roads, canals, pumping stations, pressure tubes, hydrants). The infrastructure—which is designed for a technical capacity to irrigate two-thirds of the irrigation area simultaneously—is operated by the association's staff, who makes daily decisions about the distribution of the treated water on the farmer's cropland. Continuous water supply via irrigation is indispensable for cultivating crops in the region, since the sandy soils suffer from a climatic water balance deficit [94] and have a low water retention capacity [95]. The main crops cultivated by the farmers in the irrigation area are maize, wheat, sugar beets, and rye.

Nutrient-rich sewage sludge is another output of the treatment process which is added to the irrigated wastewater during the vegetation period. The sewage sludge accrued during the winter season is dewatered, stored, and spread as fertilizer in summer on croplands in the greater Braunschweig area. The reuse scheme includes a biogas plant which is operated by the association and which uses energy crops produced with wastewater and dewatered sludge as feedstock for its operations.

Figure 3 shows the simplified value chains of the reuse scheme and how they are linked by the physical transactions and activities associated with the agricultural wastewater and sludge use. The figure shows the outputs from the treatment of wastewater, including treated wastewater and sewage sludge. These outputs are further processed in the value chain of wastewater and sludge treatment before they are reused as inputs in the value chain of crop production for producing food and energy crops. The energy crops produced with wastewater and sludge are inputs for producing electricity and heat in the value chain of bioenergy production. In this way, the material flows of value chains are linked based on the reuse of treated wastewater and sludge. Figure 3 displays the actors involved, indicated by the abbreviations above the single process steps and products, as well as the focus of the analysis, indicated by the dashed line box.

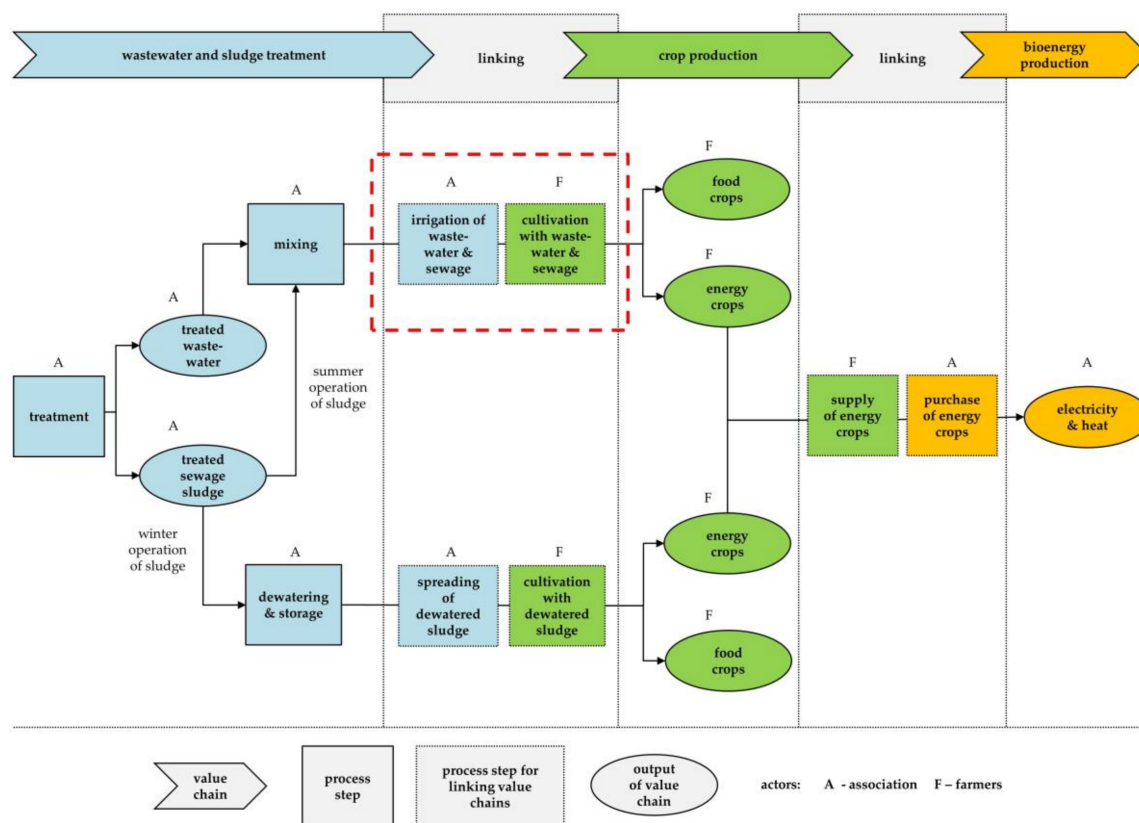


Figure 3. Linked value chains in the wastewater reuse scheme in Braunschweig.

3.2. Data Collection

The analysis draws on primary data collected between 2013 and 2016. We conducted six semi-structured in-depth interviews with eight key actors involved in the operation and management of the reuse scheme to obtain detailed information on the agricultural wastewater reuse in Braunschweig. The interviewees were carefully selected according to their roles in the reuse scheme, including farmers, managers, and employees, to learn about the topics addressed in the interviews from different perspectives.

The interviews lasted between two and four hours, and took place in the administrative buildings of the Wastewater Association Braunschweig. The interviews revolved around the operation and organization of the reuse scheme, the specific transactions and activities between the value chains of wastewater treatment and crop production, and the interests and motivations of the actors involved. In particular, the interviews focused on the properties of the transactions and activities, the interactions and interdependences between the actors, the institutional setting, and the features of the governance structures. The format of the interviews, in terms of duration and location, was chosen to give the interviewees enough time, space, and comfort to report comprehensively about the reuse scheme and respond in detail to the questions. This was done in order to facilitate a deeper understanding of the case study.

In addition to personal communication, we sent a questionnaire to the management of the association prior to the interviews for collecting data on the information exchange, communication, negotiation, contracting, monitoring, and adaptation between the actors involved in the reuse scheme. The questionnaire was to get a rough overview of the actor's interactions which we further elaborated upon in the interviews. We complemented the interviews and the questionnaire with five telephone interviews to clarify details and any open questions. The telephone interviews were conducted with some of the previously interviewed managers and employees and lasted between 30 and 90 min.

Furthermore, we conducted one face-to-face interview with three employees of the local water authority to gain information on the official permit and statutory regulations for reusing wastewater in the study area. The interview lasted 60 min, and the interviewees were selected according to their expertise in legal and practical matters of reusing wastewater. The information was supplemented by secondary data on the topic [96–98]. All face-to-face interviews were digitally recorded, and relevant parts were transcribed and summarized. During the telephone interviews, we took notes which were summarized. Table 2 provides details on all the interviews conducted within this study, including information about the date and duration of the interviews, the type of interviews (i.e., face-to-face or telephone interview) as well as anonymized information about the interviewees and their specific roles in the wastewater reuse scheme in Braunschweig.

Table 2. Description of interviews conducted with actors in the wastewater reuse scheme in Braunschweig.

Date	Duration	Type of Interview	Interviewees	Roles of the Interviewees
07.08.2013	115 min	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association; Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association; Farmer operating in the association territory
02.12.2013	150 min	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association; Deputy director of the association
			Interviewee 3	Vice chairman of the association; Farmer operating in the association territory
02.12.2013	60 min	Face-to-face interview	Interviewee 1, 2, 3	Employee of the local water authority
19.12.2013	260 min	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association; Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association; Farmer operating in the association territory
24.02.2014	80 min	Telephone interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association
23.09.2014	65 min	Telephone interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association
23.09.2014	30 min	Telephone interview	Interviewee 1	Head of the administration department of the association
28.04.2015	175 min	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association; Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association; Farmer operating in the association territory
			Interviewee 5, 6, 7	Board member of the association; Farmer operating in the association territory
27.06.2016	150 min	Face-to-face interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association
06.07.2016	175 min	Face-to-face interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association
20.09.2016	90 min	Telephone interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association
19.12.2016	45 min	Telephone interview	Interviewee 1	Head of the agricultural department of the association; Deputy director of the association

3.3. Data Analysis

The present analysis focuses on the irrigation of treated wastewater where substance flows directly link the value chains of wastewater treatment and crop production (Figure 3). We began the analysis of the interview data by elaborating upon a system of thematic categories based on the elements of our conceptual and theoretical framework to systematically structure the data. The four

main categories were (1) transactions and activities; (2) actors; (3) institutions; and (4) governance structures. These categories were subdivided into further categories also based on the elements of our conceptual and theoretical framework. The first category “transactions and activities” was split up into (i) asset specificity; (ii) uncertainty; and (iii) frequency. The second category “actors” was split into (i) tasks and responsibilities; (ii) interests; (iii) ownership and decision rights; (iv) interactions; and (v) interdependences. The third category “institutions” was split into (i) formal rules; and (ii) informal rules. The fourth category “governance structures” was divided into (i) contractual relations; (ii) incentives; (iii) command and control; and (iv) adaptations.

In the next step, we repeatedly went through the transcripts and notes and assigned all relevant text sequences to the matching categories. After this, we created additional thematic subcategories for each category according to the content of the material collected per category to further structure the data. Then, we scrutinized the transcripts and notes once again, and assigned all relevant text sequences to the matching subcategories. Finally, we identified the text sequences which were relevant for answering our research questions and summarized this material.

Building on this analysis, we continued by decomposing the sub-arenas of the agricultural reuse of wastewater and sewage sludge into different action situations. Decomposing the action arenas into different action situations allows for better understanding the multiple and complex linkages and interdependences between the value chains of wastewater treatment and crop production. After determining the case-specific action situations, we identified the specific elements of the action situations, including the focal transactions and activities, the participating actors, and their interactions. We then characterized the actors by describing their task and responsibilities, their interests, as well as their ownership and decision rights, before advancing with the four-step analysis of the discriminating alignment of transactions and governance structures as suggested by Williamson [99]:

First, we described the transactions and activities according to their properties including asset specificity, uncertainty, and frequency for better differentiation and uncovering the needs for regulation and coordination. In addition, we described the interdependences between the actors resulting from the transactions and activities; Second, we characterized the actor’s contractual relations and scrutinized the governance structures in terms of the provision of incentives, the use of administrative control, and the capacity for autonomous and coordinated adaptations; Third, we worked out the efficiency of alignment between the governance structures and the properties of the transactions and activities according to the transaction cost theory. In other words: We assessed which governance structure would match the case-specific properties of the transactions and activities best. We focused on the condition of asset specificity, since it is the most important property for determining what governance structure minimizes transaction costs [75]. Fourth, we ascertained whether the expected alignments of the governance structures with the properties of the transactions and activities as derived from the theoretical framing are corroborated by our findings. Next, we analyzed how the properties of the transactions and activities including the interdependences between the actors shape the governance structures. Finally, we evaluated how the alignment of the governance structures with the relevant properties of the transactions and activities, including the interdependences, contributes to the smooth operation of the wastewater reuse in the studied case.

4. Results

The results section is structured according to the analyzed action situations identified on the basis of our conceptual framework and the information obtained from the interviews. First, we describe the actors participating in the different action situations with their interests, interactions, and their ownership and decision rights. Then, we characterize the focal activities and transactions by their properties, and determine the governance structures that would minimize transaction costs according to the discriminating alignment hypothesis. We then describe the existing institutions and characterize the governance structures by their features.

Drawing on our conceptual framework and the information obtained from the interviews, the analysis revealed the following three focal action situations that take place in the action arenas of the agricultural reuse of wastewater in Braunschweig (Figure 4).

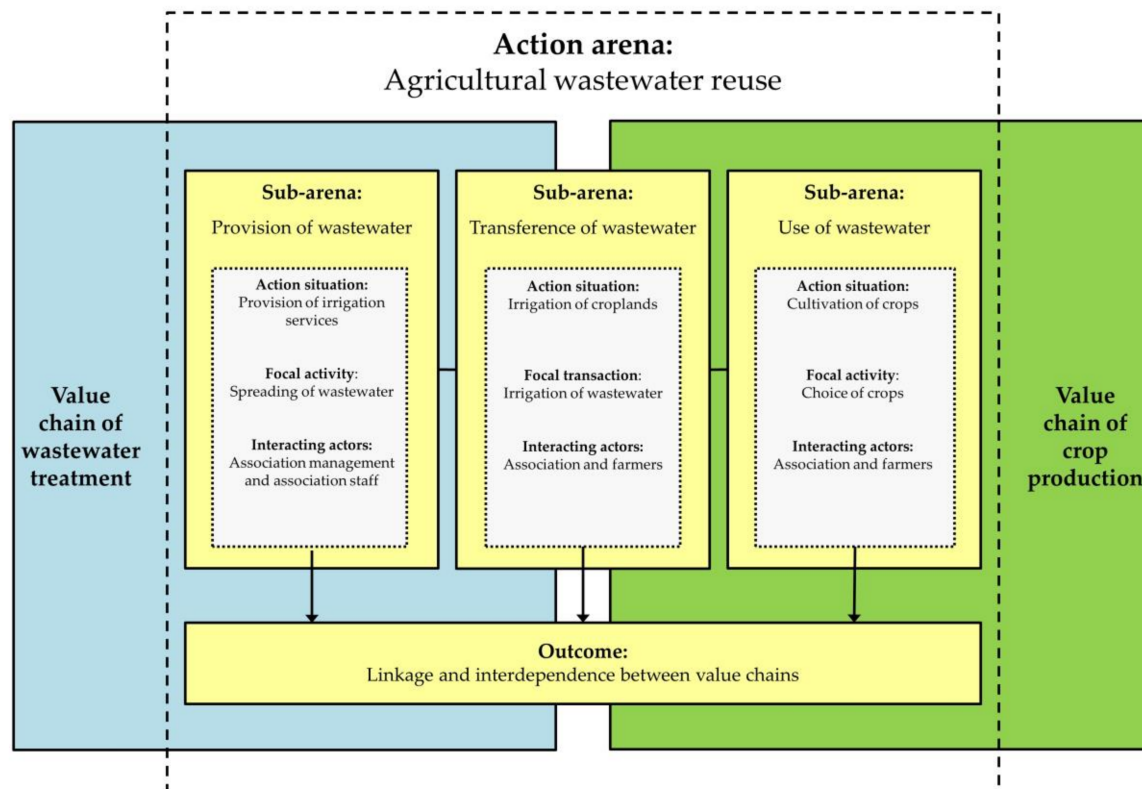


Figure 4. Action arenas and action situations of the agricultural wastewater reuse in Braunschweig.

The focal situation in the arena of wastewater provision is the provisioning of irrigation services for crop cultivation including the spreading of wastewater as the focal activity of the association staff. In this situation, the association management interacts with the association staff regarding the practical implementation of the spreading operations.

The focal situation related to the transference of wastewater between wastewater treatment and crop production is the irrigation of croplands with the irrigation of wastewater as the focal transaction between the association and the farmers. In this situation, the association interacts with the farmers regarding the provision of land and irrigation services as well as the distribution of the water and other practical matters of irrigation (e.g., schedule).

The focal situation in the arena of wastewater use is crop cultivation with wastewater, including the choice of crops a principal activity for farmers. This activity is influenced by the interaction between the association and farmers regarding the crops and cropping patterns on the irrigation fields. The joint outcome of the physical and social processes in the three arenas and situations is the linkage and interdependence of the value chains of wastewater treatment and crop production.

4.1. Provision of Irrigation Services

4.1.1. Actors and Actors' Rights

The actors involved in the provision of irrigation services include one manager of the association, six *rainmasters*, and twelve workers. The manager determines the dates for starting and ending the irrigation of certain crops (e.g., maize and sugar beets), as well as adding sewage to the irrigated

wastewater. The *rainmasters* are in charge of implementing the decisions of the manager and coordinating the irrigation operations on site. They set up the schedules for the workers and decide about the distribution of the water, based on parameters such as the soil conditions and the development of the crops. The workers, whose task is to operate the irrigation machines, perform the operations only according to instructions from actors in the upper levels of the associations' hierarchy i.e., the *rainmasters* and the manager. All assets used by the association staff for providing irrigation-related services belong to the association. Neither the manager nor the *rainmasters* or the workers hold rights of ownership of the assets used for the operations. The interactions between the manager, the *rainmasters*, and the workers are driven by the interest of the association to spread the wastewater for reuse in a proper way without causing damage to the farmers, the residents, and the environment.

4.1.2. Focal Activity

The activity of spreading wastewater is characterized by a relatively high frequency of about seven to eight times throughout the vegetation period. The physical infrastructure (e.g., canals, pumps, pressure tubes, hydrants, irrigation machines) for spreading wastewater is highly specific in its use and site, as it cannot be easily moved nor used for other purposes.

The spreading of wastewater causes interdependences between the association and the farmers, since the crop yields of the farmer's depend, among other factors, on the ability of the association staff to spread the wastewater and sewage in a safe way without damaging crops and soils. The association has built up a good reputation for the safety and quality of the spreading operations. This reputation is indispensable to maintaining the trust of the farmers in the association and wastewater cultivation. The skills and experiences of the personnel operating the irrigation system are not specific to the spreading of wastewater as they may be easily utilized for similar activities in the agricultural sector.

4.1.3. Institutional Arrangements

Institutions and governance structures regulating the spreading of wastewater need to secure the safety and high quality of the related operations. The high specificity of the physical infrastructure and the special reputation of the association regarding the safety and quality of the spreading, raise the expectation that hierarchical governance could be an efficient solution to coordinating the interactions between the association management and the association staff regarding the operation of the spreading. In the following, we will characterize the institutions and governance structures in terms of the contractual arrangements, incentives, command and control, and adaptability.

The contractual arrangements between the association management and the association staff performing the spreading is based on long-term employment contracts, which are typically incomplete, as they only stipulate the basic conditions of the employment, including the general working tasks and remuneration. Potential conflicts between the association management and the staff regarding the spreading (e.g., improper operations) are settled internally within the association without involving courts or arbitrators.

The incentive intensity for the manager, the *rainmasters*, and the workers was found to be weak because the actors cannot personally lay claim to the benefits from cost savings or efficiency improvements in the spreading.

Administrative command and control is the predominant steering mechanism as the association manager and the *rainmasters* direct the operations related to the spreading of wastewater and instruct the workers by means of commands transmitted in the form of oral and written instructions. Administrative control, including monitoring activities and outcomes, is strong in order to ensure that operations are carried out in accordance with the legal regulations, and that the workers maximize their efforts in the interests of the association.

In terms of the adaptability, we observed that the manager arranges the adaptation of the spreading operations to any changes in the legal framework or technical matters. On the fields,

the *rainmasters* are in charge of coordinating the adaptations of the operations (e.g., the adaptation of the schedules for the irrigation) to the weather and soil conditions, to the development of the crops and to ongoing cropping activities of farmers like pest management and fertilization. The capacity for coordinated adaptations is strong, due to the formal authority of the association manager and the *rainmasters* to direct the workers' spreading activities.

4.2. Irrigation of Croplands

4.2.1. Actors and Actors' Rights

The actors involved in the action situation of cropland irrigation are the association and the farmers. The relationship between the association and the farmers is characterized by separated ownership and decision rights. The association owns the wastewater and the infrastructure of the irrigation, while the farmers own or lease the land of the irrigation fields. The manager responsible for irrigation has the authority to decide about the dates for starting and ending the irrigation of certain crops (e.g., maize) without consulting the farmers, but generally asks board members of the association with agricultural background for advice. The *rainmasters* who implement the decisions of the manager decide about the sequence of the fields to be irrigated. They make the decisions about the sequence independently from the farmers, but coordinate individual irrigation schedules with the farmers. The interactions between the association and the farmers are driven by the complementary interests of the association to release the wastewater and sewage for its reuse into the farmer's fields and the interests of the farmers to obtain irrigation services and nutrient-rich water from the association for cultivating crops.

4.2.2. Focal Transaction

The irrigation of wastewater as a transaction between the association and the farmers is characterized by the high frequency of the operations and the high specificity of the physical infrastructure as described in Section 4.1.2. Another characteristic of the irrigation transaction is the site specificity of the irrigated fields because of their immovability and proximity to the wastewater treatment plant. Natural rainfall, evapotranspiration rates, crop growth, and soil conditions are nature-related sources of uncertainty that determine the optimal quantity and timing of wastewater applications. In dry periods, the crops may experience water stress if rainfall and wastewater are less than required. In wet periods, the water supply from rainfall and irrigation may exceed the maximum water absorption capacity of the crops and soil. An oversupply of wastewater increases the risk of crop damages and excessive inputs of nutrient and pollutants into soils, groundwater, and adjacent water bodies. The capability of the association to suspend irrigation is limited since wastewater is produced continuously.

The irrigation transaction establishes a relationship of interdependence between the association and the farmers based on the complementarity of the resources of water and land, the specificity of the irrigation infrastructure, as well as the mutual influence between the activities of crop cultivation and wastewater irrigation. On one hand, the association depends on the cooperation with the farmers, since the access to their fields is indispensable to releasing the wastewater for its reuse. Furthermore, the production value of the irrigation infrastructure would decrease if the farmers were to take land away from the irrigation area or refuse to irrigate their fields. On the other hand, the farmers depend on the cooperation with the association, since the provision of water and irrigation services by the association are essential for securing the profitability of cultivation under unfavorable natural conditions. Other matters that produce interdependences between the association and the farmers are related to the technical capacity of the irrigation equipment and the practice of adding sewage to the wastewater. The limited capacity of the irrigation equipment affects cultivation as it requires cropping patterns that include a variety of crops with different temporal demand for water. The practice of

adding sewage to the wastewater affects cultivation, since the nutrient loads contained in the sewage are an important determinant for the farmer's individual fertilization management.

4.2.3. Institutional Arrangements

Institutions and governance structures regulating the irrigation of wastewater need to know the irrigation area in its size and coherent structure, and secure access for the association to carry out irrigation-related operations on the farmer's land. Furthermore, institutions and governance structures need to regulate the financial contribution of the association members to cover operating costs, as well as the distribution of available wastewater among the farmers, especially in cases of mismatches between the demand and supply of water.

The properties of the focal transaction suggest that a hybrid governance structure or hierarchical forms of governance are more efficient than the spot market for coordinating collaborative interactions between the association and the farmers regarding the provision of land, water, and irrigation services. Next, we will characterize the actual institutions and governance structures with respect to the contractual arrangements, incentives, command and control, and adaptability.

The preservation of the irrigation area in its size and coherent structure is secured by the permanent affiliation of the irrigated fields to the association. Farmers who want to withdraw land from the irrigation scheme have to ask the association for permission, and they are generally required to provide compensatory areas and to compensate the association for investments, as well as to finance new investments for wastewater reuse on the compensatory areas.

The interactions between the association and the farmers regarding the provision of land and irrigation services are regulated by the *Statute of the Association*. The *Statute of the Association* defines the specific tasks of the association, clarifies the affiliation of the irrigated fields to the association, and regulates how tasks and responsibilities are shared between the association bodies. Furthermore, the statute clarifies the right of the association to use the land of the farmers for irrigating wastewater and determines the share of the farmers, the City of Braunschweig, and the Water Board Gifhorn for covering the costs of the irrigation operations. The financial contribution of the association members to covering the costs of the irrigation is regulated in such a way that each farmer pays a fixed fee (81 € ha⁻¹) per hectare of irrigated cropland. The remaining costs for the irrigation are assumed by the City of Braunschweig and the Water Board Gifhorn according to the quantities of wastewater produced in both cities.

The *Statute of the Association* is complemented by the *Irrigation Ordinance* of the association, which regulates the responsibility of the association for the operation of the irrigation and the liability for damages due to improper operations. The *Irrigation Ordinance* further stipulates the rights and duties of the farmers to accept wastewater and sewage, and specifies the conditions laid down for the expiry of the right to receive irrigation services.

The distribution of wastewater between the farmers competing for this resource is regulated in such a way that each farmer has a proportional claim to the total available wastewater according to the total size of croplands cultivated. In cases of water scarcity, the farmers generally accept the prioritizing of fields with particularly sandy soils. These soils have a lower water retention capacity, and hence, crops on these fields tend to suffer more and earlier from water scarcity. In periods of water surplus, the farmers accept the even irrigation of wastewater on their fields. In the event of a water surplus, the association tends to dispose higher charges of wastewater on fields with sandy soils and low clay content, since the percolation rate is higher in these fields and the risk of waterlogging and damaging crops is lower.

With regard to the substance flows, the reuse of wastewater on the croplands is subject to the official permission of the Upper Water Authority, which establishes specific rules and instructions about the quantity and quality of the wastewater, the sampling of water for analysis, and the practice of adding sewage to the wastewater [97]. The reuse of the sewage is further regulated by the legal provisions defined in the *German Sewage Sludge Ordinance* and the *German Fertilizer Ordinance*.

The provisions establish value limits for hazardous substances in the sewage, stipulate the conditions permitting applications of sewage, define bans and restrictions for the application, limit application quantities and prescribe the obligation to precisely control and document the reuse of sewage.

The contractual arrangements in the action situation of cropland irrigation are shaped by the collective decision made by the City of Braunschweig and the farmers during the foundation of the association in the year 1954, to reuse wastewater in the public interest and for the benefit of all members. No formal contracts exist between the association as a legal entity and the individual farmers because the association is obliged to reuse wastewater as a public service. Instead, transactions and interactions are regularized based on the institutions as defined in the *Associations' Statute* and the *Irrigation Ordinance*. The rules of the *Statute* and the *Irrigation Ordinance* are legitimated by the official bodies of the association, which are composed of representatives of the City of Braunschweig, the Water Board Gifhorn, and the farmers. The collective agreement between the association members including the farmers regarding the reuse of wastewater has an indefinite duration, and can only be terminated if the members do not benefit from the reuse scheme anymore, or if the association is not able to fulfill its statutory tasks. The agreements regarding the irrigation of wastewater are incomplete, since it is not possible to regulate, ex ante, all possible contingencies due to the uncertainties and complex nature of the interplay between natural conditions (e.g., weather conditions, soil characteristics, and vegetation), the technological opportunities (e.g., capacity of the irrigation equipment), and the behavior of the actors (e.g., cultivation activities of farmers). The provisions of the *Statute* and the *Irrigation Ordinance* provide that the association and the farmers resolve conflicts regarding irrigation (e.g., damages due to improper operations) through mutual consent or by arbitration, in case internal settlement fails.

The association is not allowed to generate profits from the reuse of wastewater and sewage. For this reason, the association has no claim to keeping profits from efficiency gains, but has to pass on profits to the members by reducing their financial contributions towards covering the costs. The incentives for operating efficiently result from the cost competition between the current wastewater reuse and conventional treatment procedures without wastewater reuse, as well as from the competition between the association and other wastewater associations in the region. The incentive intensity of the governance structure is therefore semi-strong.

The farmers have no possibility to direct the operations of the irrigation besides the informal agreements with the *rainmasters* about their individual schedule for the irrigation. Every irrigation operation is precisely documented, and information on the exact distribution of the wastewater and nutrients is passed on to all farmers and the supervisory authorities via internet, telephone, or in written form. Operations are also monitored by the regional chamber of agriculture, including soil and crop sampling, to assess risks to humans and the natural environment. The association and the farmers perceive the efforts for sharing information and controlling the activities of the irrigation as semi-strong.

The association and the farmers may adapt independently to changing conditions based on the existing ownership and decision rights for the land and the irrigation infrastructure. The association, for instance, does not consult individual farmers when adapting the operations of the irrigation to new technologies or regulations. However, the associations' capacity for autonomous adaptation is limited, because the farmers have the option to block any fundamental changes which affect the agricultural use of the land in the decision-making bodies of the association. The farmers are limited in their capacity for autonomous adaptations because they cannot withdraw their fields from the reuse scheme, or change the type of land use without consulting the association.

Coordinated adaptation between the association and the farmers is enabled under the current governance structure through association bodies in which the association and the farmers can discuss and agree upon joint adaptations in formal procedures. More frequent interactions between the farmers and the association workers also facilitate coordinated adaptations. The *rainmasters* and the farmers continuously consult each other when adapting the individual irrigation schedules to the weather and soil conditions, the crop growth, or the ongoing cropping activities of the farmers. Other means

supporting coordinated adaptations include the information letters of the association and the annual meetings of the members of the association. The information letters explain, for instance, changes in the legal framework and their implications for irrigation. In the annual meetings, problems such as the correlation between irrigation capacity and the cropping patterns of the farmers are explained. The influence of these information channels is limited, since they can only stimulate but not enforce adaptations. To summarize, the capacity of the governance structure to support autonomous and coordinated adaptations is semi-strong, since both types of adaptation are possible, but subjected to substantial limitations.

4.3. Cultivation of Crops

4.3.1. Actors and Actors' Rights

The farmers who receive wastewater from the association own or lease the land and the other assets (e.g., machinery) needed for cultivating crops. They are autonomous entrepreneurs who decide independently about the crops and the production methods. The farmers make these decisions based on market prices, yield expectations, and their individual business strategies. However, the farmer's freedom of choice is restricted by some of the institutions regulating the crops and cropping patterns on the irrigation fields. The interactions between the association and the farmers regarding crop cultivation on the irrigation fields are driven by the different interests of the farmers and the association. The farmers have an interest in receiving sufficient wastewater for their crops and cultivating those crops from which they expect to maximize their profits. The association wants the farmers to cultivate a wide range of different crops as this facilitates the sufficient supply of wastewater to the farmers. The association is interested in supplying sufficient wastewater to the farmers, since crop yield stability and the profitability of cultivation with wastewater are necessary requirements for the continuation of the reuse scheme from the farmers' point-of-view.

4.3.2. Focal Activity

The specificity of the farmers' machines, equipment, and know-how for cultivating crops with wastewater is relatively low, since it does not differ significantly from conventional crop production. Uncertainty exists about the farmers' individual selection of crops. The choice of crops as the farmers' focal activity is made before the beginning of the cultivation period. Individual farmers may decide to cultivate crops which are highly profitable, but are not allowed for wastewater irrigation. Farmers may further decide to produce less varieties of crops (e.g., only sugar beets and maize) to benefit from a greater share of more profitable crops in their cropping pattern. This behavior increases the risk of an excessive demand for water in certain periods of time caused by the uniform water requirement of one or more crops. Since only two thirds of the irrigation fields can be irrigated simultaneously with wastewater, the association can only supply sufficient water according to the crop needs if the farmers cultivate a variety of crops with different demands for water over time.

The cultivation with a choice of crops is characterized by interdependences between the association and the farmers. On one hand, the irrigation of nutrient-rich wastewater increases crop yields and enables the farmers to cultivate a wide variety of different crops that otherwise would be unsuited to sandy soils. On the other, it limits the farmer's options as it imposes bans on cultivating high-profit crops, such as fruits and vegetables. The farmer's choice of crops for cultivation influences the operations of the irrigation as it affects the association's capacity to meet the demand for water and to operate the reuse scheme efficiently. Pest control and fertilization also influence the operation of the irrigation, since they require the suspension of irrigation at certain times.

4.3.3. Institutional Arrangements

Institutions and governance structures coordinating cultivation with wastewater need to regulate crops and cropping patterns on irrigated fields, as well as the information exchange between

the association and the farmers regarding the farmer's crop decisions. Taking into account the characteristics of the focal activity, choice of crops, like the low involvement of specific investments, one can expect that a governance structure which is close to market governance is efficient to coordinate cultivation with wastewater.

The principle mechanism that coordinates the farmer's crop decisions is the price mechanism which indicates the current market demand for certain crops. The price mechanism is complemented by the institutions regulating cultivation in irrigated fields (e.g., cultivation bans). In fact, the farmers are not allowed to cultivate fruits and vegetables on irrigated fields, due to the sewage component in wastewater. Furthermore, farmers are required to inform the association about their individual choice of crops, and to agree with the association on their individual cultivation plan. The cultivation agreement is an informal agreement which is valid for one cultivation period only, and which clarifies what crops are cultivated by the farmers. The rules of the *Irrigation Ordinance* stipulate the right of the association to decide upon the cultivation plan if the cropping patterns proposed by the farmers cannot be aligned with the scheme's operational requirements (i.e., cropping patterns that include a variety of crops), and no agreement is reached. The association and the farmers normally resolve conflicts regarding the cultivation plan bilaterally, and with the help of the regional chamber of agriculture as an independent external arbitrator. In cases of violations of cultivation bans, the association may also use the option of resolving conflicts through the courts.

The farmers are subject to competition with other agricultural market players. The better their crops fulfill market needs and the more efficiently they produce, the higher the chance of increasing their individual profit. The incentives for the farmers to adapt to changing market demands and to increase the efficiency of their cultivation activities are therefore strong.

The options for the association to direct the farmer's cultivation activities are limited, as the association may only object to the cultivation plans proposed by the farmers, and eventually prescribe a different cropping plan on the irrigation fields, if the farmer's cultivation plans hamper the efficient operation of the irrigation scheme. Administrative control is perceived as semi-strong, and refers to the control activities of the manager and the *rainmasters* who check if the farmers adhere to the cultivation bans and the cultivation agreements. The association refuses to irrigate the fields of individual farmers as a sanction if these farmers violate the cultivation bans, or if they do not stick to the agreed cultivation plan.

The strong incentives motivate the farmers to constantly adapt the cultivation to changes in technology and the demand for certain crops. The capacity of the farmers to adapt their businesses independently from the association is high, due to the autonomy resulting from separated ownership and decision rights. Nevertheless, the capacity for autonomous adaptations is restricted, since the farmers need to consult the association about any changes in the cultivation plans as it affects the operation of the irrigation scheme. The adaptation of the farmer's cultivation plans in a coordinated way is supported by the frequent and direct contact between association staff and the farmers. This frequent and direct contact also facilitates short-term adaptations of the irrigation schedules to the farmers' current cropping activities. The capacity of the governance structure to coordinate adaptations, other than those of the farmer's cultivation plans and the adaptation of the irrigation schedules, is weak.

5. Discussion

The theoretical assumption in transaction cost economics is that governance structures are chosen to fit the specific properties of transactions and to minimize transaction costs [38,77,81]. Interdependences between actors—like in the case of the association and the farmers engaging in wastewater reuse—are believed to shape the nature and features of governance structures [81]. Understanding how governance structures are shaped by the properties of the transactions and the interdependences of actors is of utmost interest when aiming at a circular economy characterized by value chains linked through transactions.

In the following section, we verify whether the governance structures observed in the case of the wastewater reuse in Braunschweig are consistent with the governance structures expected according to the transaction cost economic theory. We start with discussing how the governance structures are shaped by the relevant properties of the transactions and activities, including the interdependences between the association and the farmers. We then determine the governance structures (i.e., market, hybrid or hierarchy) according to their features. We then discuss how the alignment of the governance structures with the properties of the transactions and activities contributes to the smooth operation of the wastewater reuse scheme. After this, we will reflect upon the lessons learned for governing transactions and interdependences between linked value chains in a circular economy. Finally, we will discuss the research design regarding its strengths and weaknesses and suggest potential directions for future research.

5.1. Alignment of Transactions, Interdependences, and Governance Structures

Based on our findings, we argue that different governance structures coordinate the transactions and activities in the action situations of the wastewater reuse scheme in Braunschweig. The provision of irrigation services with the spreading of wastewater is coordinated in a hierarchical way, and crop cultivation with the choice of crops is close to market governance. The irrigation of croplands with the irrigation of wastewater links the value chains of wastewater treatment and crop production, and displays features of a hybrid governance structure. Table 3 summarizes the main features of the governance structures observed in the focal transactions and activities of the different action situations of wastewater reuse in Braunschweig.

Table 3. Features of the governance structures for focal transactions and activities in the action situations of wastewater reuse in Braunschweig.

Features	Action Situations with Focal Transactions and Activities		
	Provision of Irrigation Services with Spreading of Wastewater	Irrigation of Croplands with Irrigation of Wastewater	Cultivation of Crops with Choice of Crops
Incentive intensity	weak	semi-strong	strong
Administrative control	strong	semi-strong	semi-strong
Autonomous adaptation	weak	semi-strong	generally strong, but restricted
Coordinated adaptation	strong	semi-strong	generally weak, but possible for certain adaptations

5.1.1. Provision of Irrigation Services

The governance structure used for coordinating the spreading of wastewater is shaped by the properties of the activity, including the specificity of the irrigation infrastructure, the good reputation of the association regarding the quality of the spreading, and the interdependence between the association and the farmers. These characteristics constitute the need for discouraging opportunism to ensure a continued provision of high quality spreading. The governance structure chosen to fit with the properties of the spreading is characterized by weak incentives, strong use of administrative command and control, as well as a strong capacity to coordinate adaptations. These features clearly indicate that the spreading is coordinated by a hierarchical governance structure. The observation of a hierarchical governance structure corresponds with the expectations based on transaction cost theory, which leads us to assume that the governance structure for the spreading was chosen in a transaction cost minimizing way, following discriminating alignment [76,77]. In particular, it becomes evident that the hierarchical governance structure responds to the high asset specificity of the activity.

The alignment of the governance structure with the properties of the spreading contributes to the smooth operation of the reuse scheme. The hierarchical coordination with weak incentives and strong administrative control prevents the association staff from behaving opportunistically. The strong

administrative control compensates the weak incentives for the association staff and stimulates good operating performance, which is indispensable to spreading wastewater without causing damage to the farmer's crops and soils. Another benefit of the alignment is that hierarchical coordination between the association staff enables the association to adapt the operations of the spreading quickly to the farmer's ongoing cropping activities, and any changes of the weather, soil, and crop conditions. Hierarchical governance structures, like the governance structure for the spreading of wastewater, are characterized by high bureaucratic costs [77]. In the studied case, it can be expected that the high frequency of the spreading helps the association to make the hierarchical governance structure more cost-effective. Furthermore, the interviewees reported that the frequency of the spreading have contributed to developing trust and well-established routines between the manager, the *rainmasters*, and the workers. This may also help to keep the transaction costs for the spreading low, since empirical studies show that trust among actors can reduce transaction costs and improve the performance of collaborative actions between actors [100,101].

5.1.2. Irrigation of Croplands

The governance structure used for coordinating irrigation is shaped by the properties of the transaction, including the specificity of the assets and the interdependence between the association and the farmers. The site specificity of the irrigation fields and the physical specificity of the irrigation infrastructure, along with the complementarity of the resources of water and land, increase the interest of the association and the farmers, to give continuity to the transaction and drive them to engage in long-term cooperation. The association thus commits to providing irrigation services, and the farmers commit to providing cropland for wastewater irrigation. On the operational level, the interdependence leads to an increased need for administrative control, including the necessity for monitoring operations and sharing information on the activities of irrigation and cultivation. In particular, the actors need to share information on the distribution of wastewater and nutrients, as well as the individual schedules for the activities of irrigation and cultivation. The interdependence further results in restrictions for autonomous adaptations, and the necessity to coordinate certain adaptations, such as suspending irrigation when farmers carry out pest management or fertilization measures. Last but not least, interdependence leads to the association and farmers resolving conflicts bilaterally or through arbitration, since conflict settlement via courts is not conducive to preserving mutual trust and the continuity of the spirit of cooperation.

The governance structure chosen to match with the properties of the irrigation is characterized by pooling resources with separated ownership and decision rights (e.g., land and irrigation infrastructure), incomplete contracts (e.g., absence of formal contracts) and competition between resource users (e.g., farmers regarding the available wastewater) and between other forms of organization (e.g., competition of the association with other wastewater associations). From these empirical observations, we conclude that the governance structure for irrigation corresponds to a hybrid governance structure. This finding is underpinned by the observation of semi-strong incentive intensity, semi-strong use of administrative control, and semi-strong capacity for autonomous and coordinated adaptations. The observation of a hybrid governance structure is consistent with the governance structure expected according to the transaction cost theory, which leads us to assume that the governance structure for irrigation is able to sufficiently economize transaction costs.

The alignment of the governance structure with the specificity of the irrigation and the interdependence between the association and the farmers facilitates the smooth operation of the reuse scheme. The long-term cooperation between the association and the farmers based on the permanent affiliation of the irrigated fields to the association helps to protect the investments of the association against the potential opportunistic behavior of farmers. The monitoring of operations and the information sharing, regarding the substance flows and the activities of the irrigation and cultivation, facilitates the integration of wastewater reuse into cultivation, by making actions and activities more transparent and predictable. The restriction of autonomous adaptations prevents

possible independent actions of the association and the farmers from negatively influencing the cultivation and operation of the reuse scheme. The support of coordinated adaptations helps to achieve mutual consent among the association and the farmers about any adaptation of the irrigation operations to changes in the natural conditions, the cultivation plans, or the cropping activities. Last but not least, the use of arbitration, in cases where bilateral conflict resolution has failed, has proven to be efficient in solving conflicts and enhancing the legitimacy of actions.

5.1.3. Cultivation of Crops

The governance structure used for coordinating the choice of crops is marked by the uncertainty regarding the activity and the interdependence between the association and the farmers. This results in the farmers sharing information on their choice of crops and formulating agreements with the association on cultivation plans. The need for administrative control, including the need to monitor cropping patterns and to sanction violations of cultivation bans, is a further result of the uncertainty and the interdependence between the association and the farmers. Other implications of the interdependence for the governance structure include the need to restrict autonomous adaptations of the farmer's cultivation plans and to coordinate the respective adaptations.

The governance structure used for coordinating the cultivation with wastewater shows features that are typical for market governance, like separated ownership rights, strong incentives, and the support of autonomous adaptations. Other features, such as the semi-strong use of administrative control, the restrictions for autonomous adaptations, the possibility of coordinating certain adaptations, as well as the right of the association to prescribe the cultivation plans of the farmers, are not typical for pure market governance structures, and display features of hybrid or even hierarchical governance structures. In general, market governance corresponds to prior expectations on the basis of the low asset specificity in the activity. In addition, the governance structure matches with the uncertainty and the interdependence by adopting hybrid and hierarchical features into the governance structure. This leads us to assume that the governance structure is in line with the properties of the activity, and is able to keep transaction costs low.

The alignment of the governance structure with the uncertainty and the interdependence between the association and the farmers results in various benefits which contribute to the smooth operation of the reuse scheme. The sharing of information and the agreements on the cultivation plans reduce the uncertainty regarding the farmer's choice of crops, and allow for better planning of the operations of irrigation. This helps the association to organize the operations efficiently, and to supply sufficient water to all farmers. The monitoring of the cropping patterns and the practice of sanctioning violations of cultivation bans discourages farmer opportunism. The consultations between the farmers and the association regarding the adaptations of the cultivation plans hinder autonomous actions of farmers, that may reduce the efficiency of the reuse scheme due to misalignments between the adapted cultivation plans and the scheme's operational requirements. Furthermore, the consultations regarding the adaptations of the irrigation schedules to the farmers' cropping activities prevents the operations of irrigation and cultivation from interfering with one other.

5.2. Lessons Learned and Contribution to the Literature

Several lessons for governing transactions and interdependences between linked value chains in circular economies can be derived from the study of the wastewater reuse scheme in Braunschweig. The study shows that reusing wastewater in agriculture involves various transactions and activities which are characterized by specific properties. The transaction of wastewater irrigation creates interdependences between the association and farmers, which significantly shape the design of the governance structures in the reuse scheme. In particular, the findings show that interdependences can result in an increased need for administrative control, including the monitoring of activities and mutual information sharing between interdependent actors. Furthermore, the study shows that dealing with interdependences requires governance structures that can restrict autonomous adaptations and

support coordinated adaptations, and bilateral conflict resolution between interdependent actors. In theory, these requirements can be best fulfilled by features typical for hybrid and hierarchical governance structures. In practice, we found that the governance structures correspond with the expectations based on theoretical thinking. In particular, the governance structure for the choice of crops exhibits features of hybrid and hierarchical governance structures, even though market governance is still the predominant governance structure for the activity, due to the low asset specificity. This may indicate that the condition of asset specificity remains the most important characteristic for determining the choice of governance [75]. However, it may also indicate that linking value chains for reusing wastewater drives market governance structures to adopt features of hybrid and hierarchical governance structures to better cope with interdependences resulting from transactions.

Referring to the case of reusing wastewater in agriculture, we conclude that different governance structures are needed to match the different properties and requirements of the transactions and activities between linked value chains. Another conclusion we draw from the case study is that interdependences resulting from transactions increase the need for coordination between actors. Interdependences between actors should be identified and taken into account when developing appropriate governance structures for transactions between linked value chains. Last but not least, we conclude that aligning governance structures with the properties of transactions and activities potentially contributes to efficiently governing transactions and interdependences between linked value chains. A better understanding of the governance structures for coordinating transactions and interdependences between linked value chains is important for developing circular economies [9,22]. Therefore, we believe that the lessons learned from the wastewater reuse scheme in Braunschweig can also enhance solution findings related to the governance of circular economies characterized by linkages and interdependences between value chains.

Our research contributes to the literature in several aspects: First, it provides a detailed characterization of the specific transactions and governance structures for reusing wastewater at the local level. Second, our study helps to understand how transactions and interdependences between actors shape the governance structures for wastewater reuse at the local level. Third, our study provides valuable insights in how the alignment of the governance structures with the transactions and interdependences of actors contributes to the smooth operation of agricultural wastewater reuse schemes. In this way, the study facilitates the understanding of governance structures for coordinating the specific transactions and activities that create linkages and interdependences between the value chains of wastewater treatment and crop production.

The findings of the study could be of use to practitioners involved in wastewater reuse schemes and for stakeholders concerned with future wastewater management practices, and the transition towards the circular economy. We believe that the findings can assist in developing appropriate governance structures for transactions between interdependent value chains, which, in turn, can help practitioners, like wastewater providers and farmers, take advantage of the economic and environmental benefits of reusing wastewater and the circular economy.

5.3. Research Design and Future Research Directions

The results of our analysis refer specifically to the case of reusing wastewater in agriculture, and may not be simply generalized or transferred without critical reflection upon other cases of linking value chains in the circular economy. However, the conceptual, theoretical, and analytical framing used in this study may potentially also be applied for studying transactions and interdependences between value chains from other sectors.

The conceptual and analytical approach of decomposing the agricultural reuse of wastewater into different action arenas and action situations proved to be a suitable guideline assistance for investigating the transactions and interdependences between the value chains of wastewater treatment and crop production. In particular, this approach helped us to better structure the analysis and to break down the complexity of reusing wastewater into manageable sets of practical activities.

The theory of transaction cost economics proved to be expedient for explaining the choice of the governance structures for the focal transactions and activities within the action situations of our conceptual framework. However, the theory is static in nature, and thus might be less useful when it comes to explaining the impact of dynamics between actors and transactions on the governance structures. The theoretical explanation of the impact of dynamic issues would facilitate future studies on linked value chains in a circular economy, since the transition from the linear economic model towards the circular economy is a dynamic process, and the characteristics of actors and transactions may change and require different governance structures over time.

Regarding the analysis of the properties of the transactions, we focused on the conditions of asset specificity, which is considered by Riordan and Williamson [75] as the most important transaction property. Furthermore, we analyzed the conditions of uncertainty and frequency. Other authors suggest taking into account further transaction properties in order to increase the analytic content of transaction cost analysis in socioecological systems like agriculture [102,103]. Hagedorn et al. [102], for instance, proposes the inclusion of, among others, the excludability of actors, the rivalry among resource users, the degree of complexity, separability or jointness, as well as the measurability of the cost and benefits when analyzing nature-related transactions. These properties may also be relevant for the studied case, and can add explanatory power to the observed choices of governance structures.

The methods applied in this study are subject to the general limitations of qualitative research, including the more complex collection and interpretation of data, the lower robustness of the data, as well as the limited generalizability of the results [90,91,104]. However, we argue that using a case study and semi-structured face-to-face interviews to study the transactions and interdependences between linked value chains, in depth, was appropriate for answering the research questions. We acknowledge that more empirical work on the governance of wastewater reuse schemes is needed to prove whether the findings remain valid in other cases of combining wastewater treatment and crop production.

Future research may address the challenge of measuring the cost and benefits from aligning the governance structures with the transactions and interdependences. We did not measure the costs and benefits in nominal terms, since the data required for conducting a quantitative transaction cost analysis could not be provided by the actors of the reuse scheme. Our approach is in line with many other empirical studies which confine transaction cost analysis to an application of the discriminating alignment hypothesis [71,93,103,105]. Another suggestion for future studies is to focus on the dynamics in linked value chains, and to take into account the development of the characteristics of the actors, the transactions, and the governance structures over time. In addition, future work may elaborate on the specific characteristics of the interdependences between actors in linked value chains. This could include a more detailed analysis of how the degree and the type of interdependence (e.g., resource-based, technical, operational, economic) influence the choice of the governance structures.

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